# Effect of Electric Shock on the Heart *

By L. P. FERRIS, B. G. KING,† P. W. SPENCE and H. B. WILLIAMS †

AS a basis for the development of protective measures and practices, knowledge of the limits of dangerous electric shock is obviously important and this joint investigation at the College of Physicians and Surgeons of Columbia University was initiated in the hope of obtaining some of the needed data. In seeking a value of current which if exceeded would be dangerous to man, it is important to consider for different practical conditions the effects which are brought about as the current is increased. The threshold of sensation is reached at about one milliampere for a frequency of 60 cycles. Other investigators have found that at about 15 milliamperes from hand to hand the subject becomes unable to control the muscles subjected to stimulation.

Any currents that prevent voluntary control of the skeletal muscles are dangerous because their pathway through the body might include the respiratory muscles and stop breathing during the shock. If prolonged, asphyxial death would result, but the time required is a matter of minutes rather than seconds, so that opportunity may be afforded for action to release the victim. No serious or permanent after-effects are likely to appear merely from the cessation of respiration, provided it is not continued beyond the point where the victim can be resuscitated by artificial respiration.

Currents somewhat greater than those just necessary to stop respiration by action on the muscles may cause fatalities, even though the duration of such shocks is but a few seconds or less—far too short to be important from the standpoint of interruption of respiration and obviously too short to give any opportunity for rescue before the end of the shock. Death under such conditions is brought about by ventricular fibrillation, which is a disruption of normal heart action. This condition is an uncoordinated asynchronous contraction of the

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† Drs. H. B. Williams and B. G. King, joint authors of this paper, are of the staff of the College of Physicians and Surgeons of Columbia University, New York. Electrical facilities of the Bell Telephone Laboratories supplemented those of the Physiology Laboratories of the Medical Center where most of the experimental work was done.

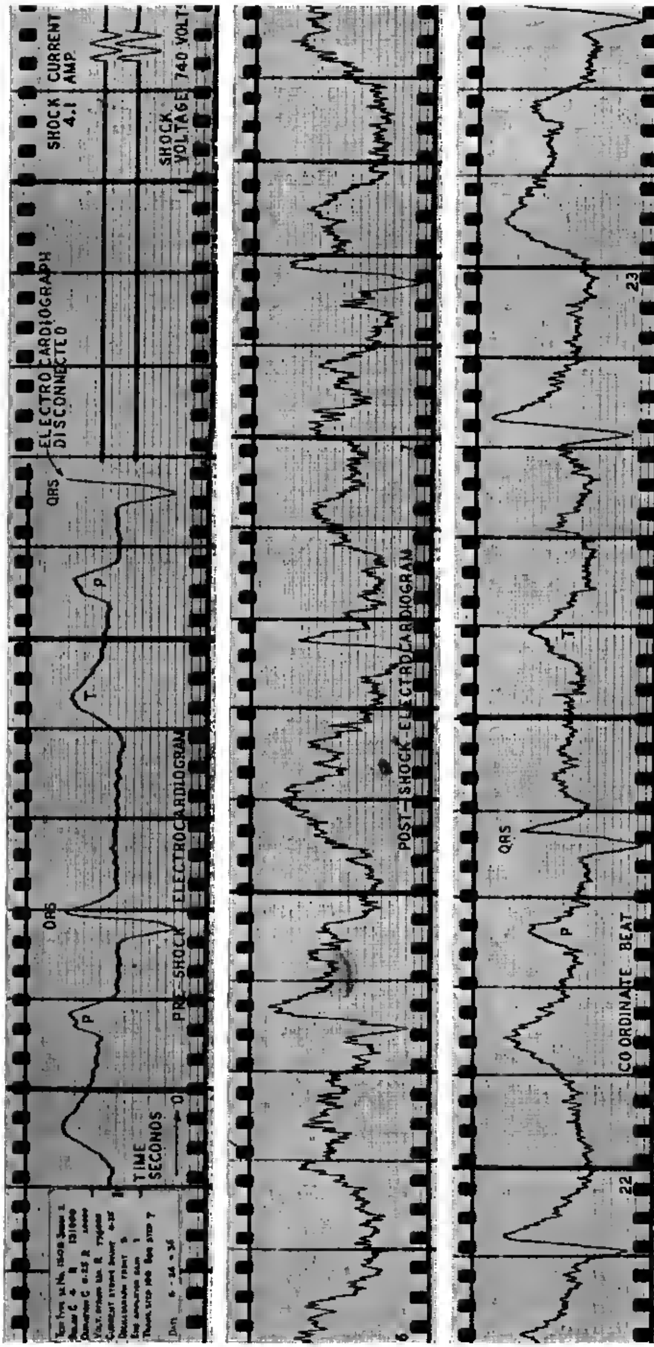


Fig. 1A—Typical records of 0.03-second shocks to sheep during insensitive phase of cardiac cycle. The electrodes were fastened to the right fore leg and left hind leg.

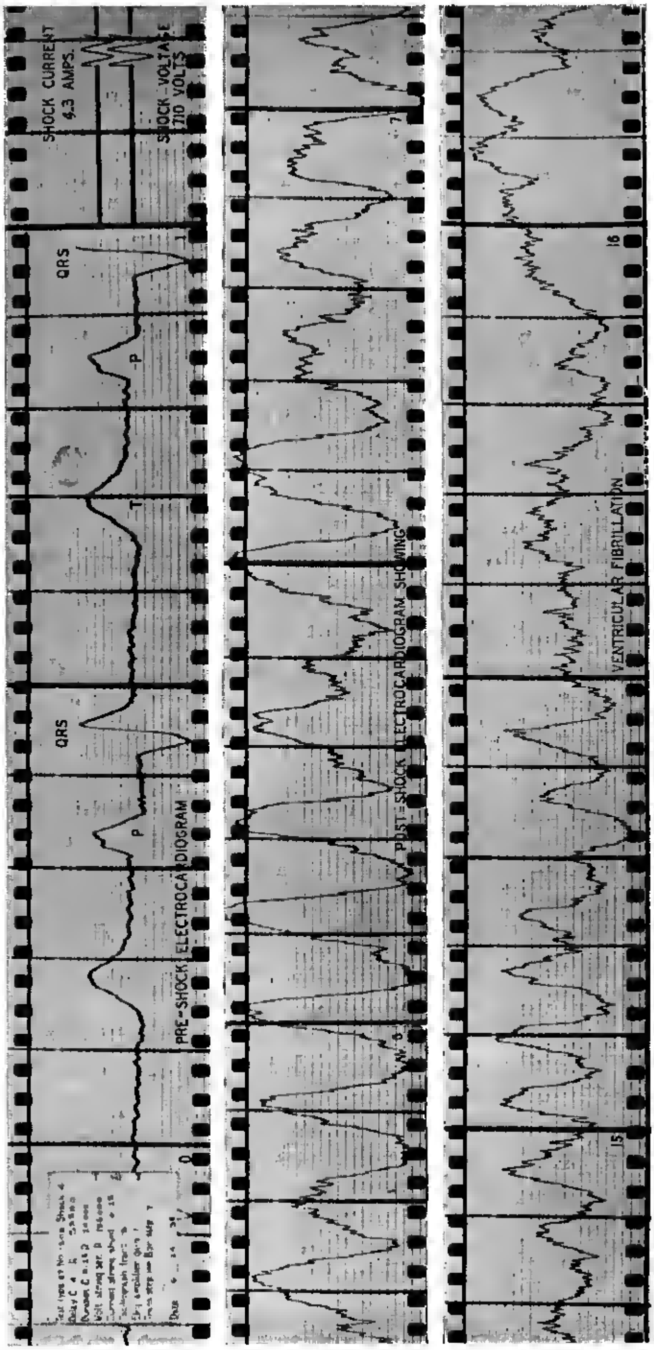


Fig. 1B—Typical records of 0.03-second shocks to sheep during sensitive phase of cardiac cycle.

ventricular muscle fibers in contrast to their normal coordinated and rhythmic contraction. It results from an abnormal stimulation rather than from damage to the heart. In the fibrillating condition, the heart seems to quiver rather than to beat; no heart sounds can be heard with a stethoscope; the pumping action of the heart ceases; failure of circulation results in an asphyxial death within a few minutes. The medical profession long has recognized that ventricular fibrillation once set up in man is unlikely to cease naturally before death. The value of current just under the threshold for ventricular fibrillation, therefore, may be taken as the maximum current to which man safely may be subjected, because regardless of rescue or after-treatment, death is liable to result from greater current.

This experimental investigation, therefore, was directed chiefly toward determining the minimum current that would initiate ventricular fibrillation and the variation of this threshold current with several factors which enter into the practical application of the results in the development of protective devices and measures. From the standpoints of both physiology and engineering, it was important to determine the influence on this threshold of:

1. Species and size of animal.
2. Path of current through the body (determined by points of contact).
3. Frequency of the current.
4. Time of occurrence of short shocks in relation to the cardiac cycle.
5. Duration of shock.

Thresholds were determined for seven species of animals: the guinea pig, rabbit, cat, dog, sheep, pig, and calf. Standard reference conditions included the use of 60-cycle alternating current for a duration of 3 seconds with electrodes on the right fore leg and left hind leg. These conditions typify those of many accidental shocks to man and are very dangerous from the point of view of ventricular fibrillation because the heart is almost directly in the current path.

Three significant records were made by an oscillograph for each shock. These are illustrated in Figs. 1A and 1B. They include electrocardiograms before and after shock and oscillograms of shock current and voltage. An electrocardiogram is a graphical record of the time variation of the voltage that is always associated with the action of the heart. The character of the variations in this voltage indicate certain facts as to the heart's condition, the electrocardiogram of a fibrillating heart being very different from that of a normal heart. The group of Fig. 1A shows a shock followed by coordinate beating. The group of Fig. 1B shows a shock which resulted in ventricular

fibrillation. The character of both post-shock electrocardiograms is somewhat masked by higher frequency currents resulting from skeletal muscle activity following the shock. However, the post-shock electrocardiogram of the group 1A reveals the same typical sequence of prominent deflections that appear before shock, while that of the group 1B shows an entirely different wave shape. The appearance of this typical fibrillating wave and the absence of heart sounds following shock were taken as conclusive evidence of ventricular fibrillation.

## Threshold of Fibrillation

The threshold current increases roughly with both the heart weight and body weight of the different species of animals, although if the three smaller species be considered alone this relationship does not hold, their threshold currents being practically the same despite widely different body weights. Data from tests on a number of different species are summarized in Fig. 2.

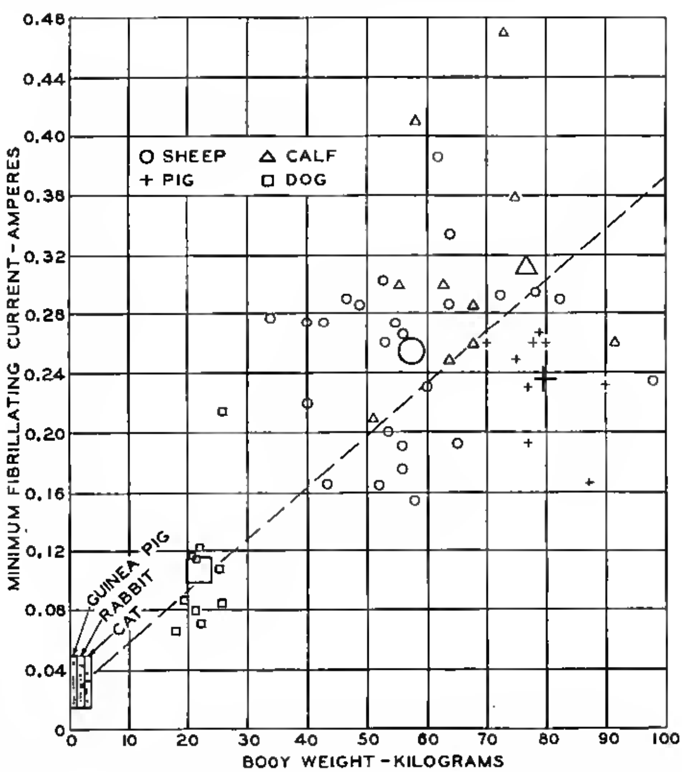


Fig. 2—Relation of minimum current causing ventricular fibrillation to body weight for different animal species. Shock duration 3 seconds. Frequency 60 cycles. Electrodes on right fore and left hind legs. (Averages shown by larger symbols.)

These results serve to indicate the probable threshold current for man under similar conditions. The average weight of an adult man is approximately 70 kilograms (154 lbs.) and his heart weight, 330 grams (.75 lbs.). The average threshold current for a body weight of 70 kilograms is 0.26 ampere and that corresponding to a heart weight of 330 grams is 0.29 ampere. Knowledge of such average currents is useful, but in the practical application of this information it is the lower limit of current causing ventricular fibrillation that must be taken into consideration. The thresholds differ widely for different individuals of the same species. The results on the whole indicate for man that currents in excess of 0.1 ampere at 60 cycles from hand to foot would be dangerous for shock durations of three seconds or more.

## Effect of Frequency

To determine the effect of changing the frequency other tests were made on sheep with 25-cycle current and direct current, the general

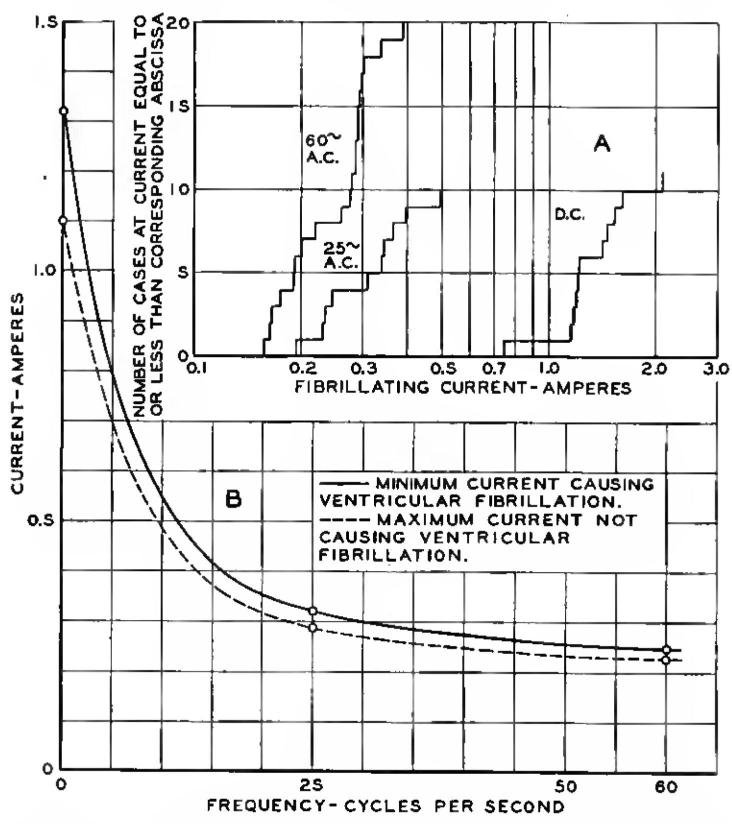


Fig. 3—Effect of frequency on threshold current causing ventricular fibrillation in sheep. Shock duration 3 seconds. Electrodes on right fore and left hind legs.

conditions remaining the same as for the 60-cycle current. The results of these tests are illustrated graphically in Fig. 3.

## Susceptibility of Heart in Different Phases of Cardiac Cycle

Physiologists have established that the heart is responsive to moderate electrical stimuli during the period of relaxation (diastole) whereas such stimuli during the period of contraction (systole) do not elicit further response. During early systole (*QRS* to beginning of *T*, Fig. 1) the heart muscle is totally unresponsive, while during diastole (end of *T* to beginning of *QRS*) the ventricular muscles are responsive to stimuli. At the time of the *T* wave of the electrocardiogram, contraction starts to disintegrate and parts of the ventricular muscle will respond differently to electrical stimuli. In view of these facts and some erratic responses to shocks of three to four cycles of 60-cycle current, differences were expected in the response of the heart to very short shocks during different phases of its cycle. Special apparatus was developed for applying short shocks at predetermined parts of the cardiac cycle. The results of 913 shocks of 0.03-second duration on 132 sheep are plotted in Fig. 4, to show the position of the mid-point of each shock in the cardiac cycle, approximate shock current and whether or not fibrillation occurred. None of the shocks occurring during the period of complete contraction or complete relaxation of the heart caused ventricular fibrillation, this result appearing only for shocks falling during the period of diminishing contraction.

Of 370 shocks of 0.12 second duration applied to 38 sheep, only one shock definitely outside the partial refractory phase resulted in ventricular fibrillation. This shock began at a point in the electrocardiogram between *P* and *Q* waves at which time the ventricles are completely relaxed and resting.

## Effect of Duration

In the determination of thresholds for shocks of very short durations, a third or less of the duration of one heart beat, the time of occurrence of the shocks was regulated so as always to involve the partial refractory phase, corresponding to the appearance of the *T* wave. The thresholds were found in the same way as for 3-second shocks, by applying successive shocks at intervals of 5 minutes, each at increased current until ventricular fibrillation resulted.

The effect of duration on the threshold is illustrated in Fig. 5. It is believed that the current required to initiate fibrillation would increase markedly as the duration is decreased below 0.03 second. It

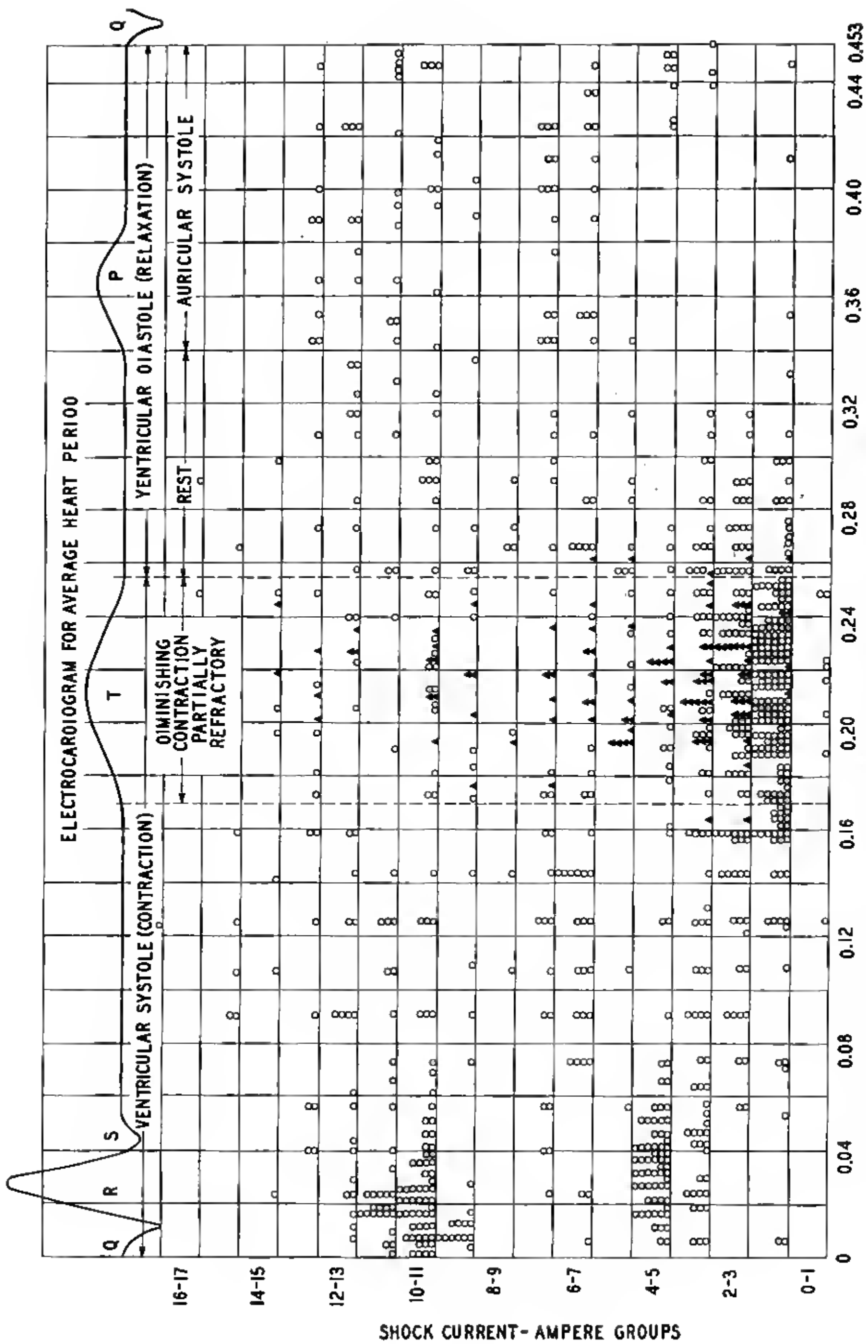


Fig. 4—Distribution in cardiac cycle and results of 913 shocks of 0.03-second duration to 132 sheep. 60 cycles. Electrodes on right fore and left hind legs. Triangle indicates fibrillation. Circle indicates coordinate beat.

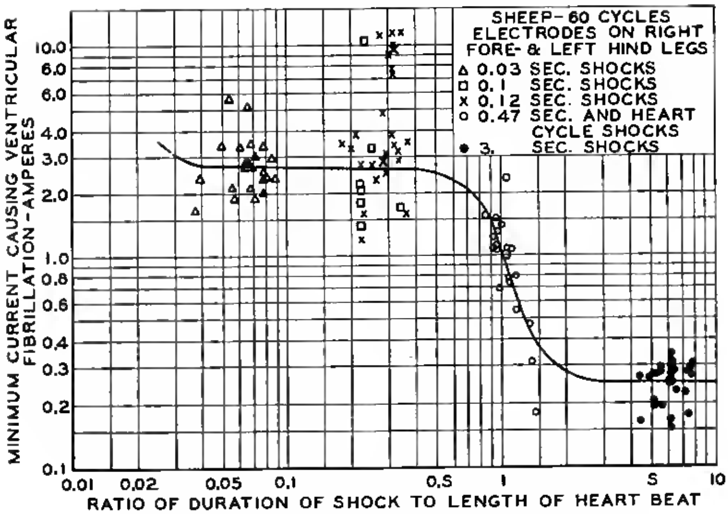


Fig. 5—Effect of duration on threshold.

is, however, not believed that increasing the duration beyond 3 seconds would reduce the average threshold current appreciably below 0.25 ampere.

Ventricular fibrillation has been found to be the only serious cardiac effect of the currents applied in these tests; however, temporary disruptions of normal cardiac activity frequently can be observed. A most common effect of electric shock is a change in heart rate. Electrocardiograms after shock frequently indicate disturbances of conduction in the heart. Premature heart beats (extrasystoles) and fibrillation of the auricles have also been observed.

The persistence of any of these conditions for more than a few minutes is rare. There is no evidence of any cardiac abnormalities or the presence of cardiac damage in electrocardiograms taken at intervals up to two months following shocks which did not immediately cause death.

## Effect of High Currents

There was evidence from the work of Prevost and Battelli and some of the early results of this investigation that the stimulus of a powerful current would be less liable to cause fibrillation than a current moderately above the threshold. To test such evidence repeated short shocks of 23 to 26 amperes were given to a group of sheep in the sensitive phase of their cardiac cycle. Ten survived 5 shocks each without fibrillation, while an eleventh fibrillated on the initial shock. Each of the 10 surviving sheep was given additional similar shocks,

except that the current was reduced to between 4 and 5 amperes. Five developed ventricular fibrillation on the first shock, and 3 on the second shock. A single animal survived 5 shocks, and another animal 2, without fibrillating. A comparison and combination of these results and those previously obtained definitely establish that the susceptibility of the heart to ventricular fibrillation becomes very much less when the current is increased to about 25 amperes, 10 times the average threshold value for shocks of short duration. This variation of susceptibility to fibrillation is shown graphically in Fig. 6.

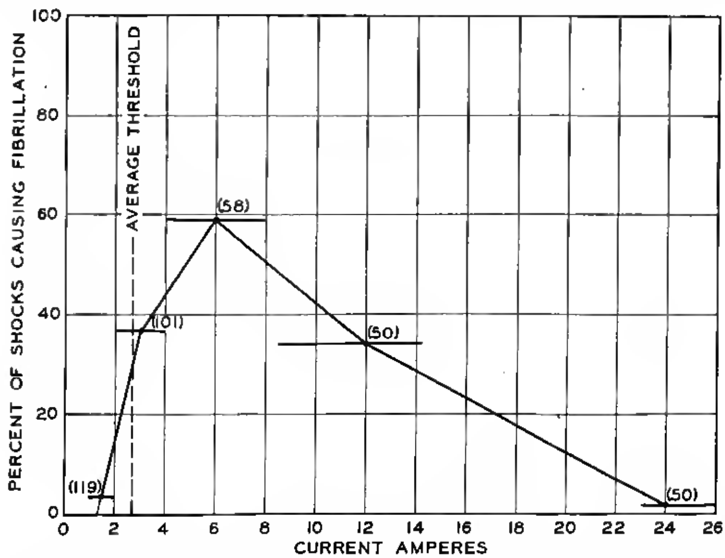


Fig. 6—Effect of current on susceptibility of sheep hearts to ventricular fibrillation. Shocks of 0.03 second, 60 cycles, applied in partial refractory period of cardiac cycle. Number of shocks and current spread indicated for each point on curve.

To determine whether such a decrease in susceptibility to fibrillation would occur also for shocks of about 3 seconds duration if the current were increased about 15 times the average threshold, 5 sheep were subjected to 4 ampere shocks of 3 seconds duration. In all cases ventricular fibrillation resulted on the initial shock, indicating either that at this duration no such decrease in susceptibility takes place with increase of current, or that 4 amperes is not a sufficiently high current to bring it about. The apparatus was not capable of giving much higher currents for this duration.

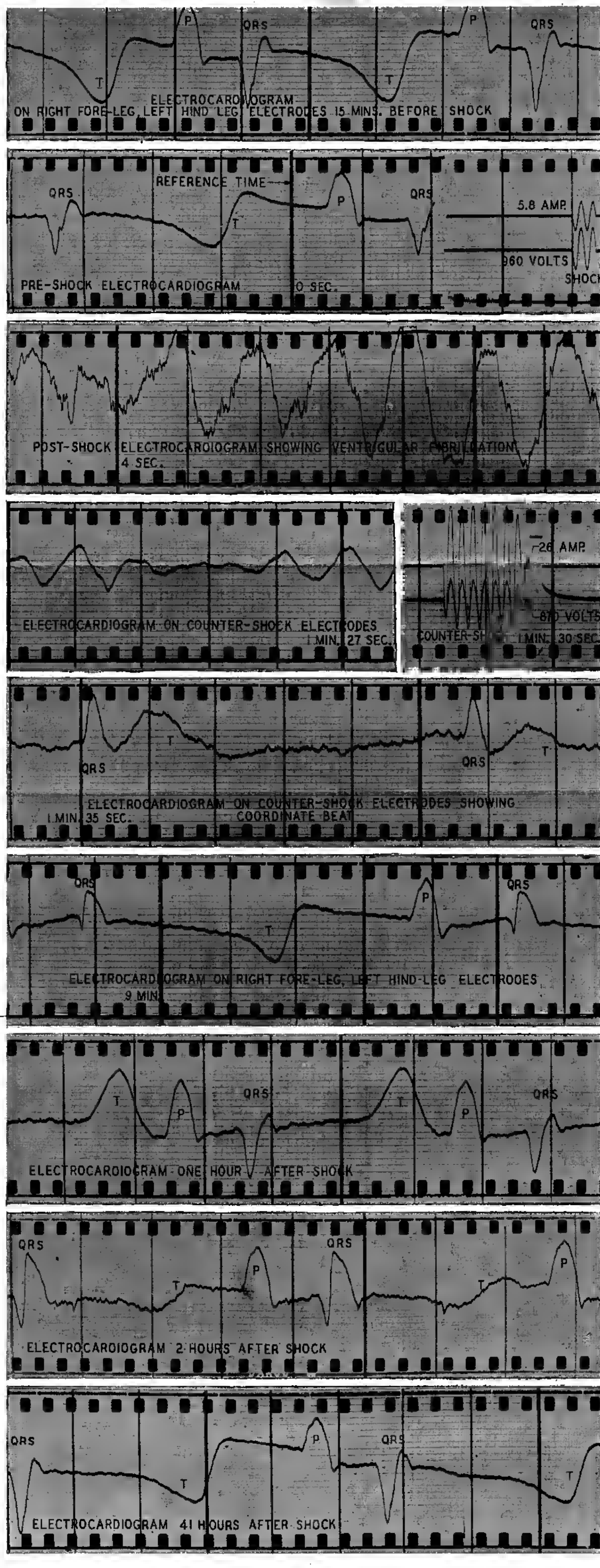


Fig. 7—Record of restoration of heart from ventricular fibrillation by a counter-shock.

## Recovery of Heart from Ventricular Fibrillation

Recovery of the heart from ventricular fibrillation by the application of a short intense shock was reported first by Prevost and Battelli in 1899. Kouwenhoven, Langworthy and Hooker also have reported the recovery of dogs from fibrillation by the application of what has recently been termed a "counter-shock." The opportunity to experiment on recovery from ventricular fibrillation with large animals arose with the use of sheep and other large species in 1932. Currents up to 25 or 30 amperes were applied through large electrodes placed near the heart.

After some preliminary tests all counter-shocks were given with electrodes outside the skin on both sides of the chest so as to include the heart between them. Such counter-shocks were found to be effective in recovering coordinate heart action in about 60 per cent of the cases.

Figure 7 is an electrocardiographic record of heart action before and after a shock that caused fibrillation and at different stages after the application of a counter-shock that arrested the fibrillation and allowed the heart to resume its coordinate beating. The current and voltage of the fibrillating shock and the counter-shock are shown also to the same scale for comparison. The fibrillating shock of 6 amperes and 0.03 second duration occurred during the sensitive phase of the cardiac cycle. The counter-shock which followed 1½ minutes later was of 26 amperes for 0.1 second duration. Times marked on the different sections are referred to the beginning of the record. It may be observed that the last electrocardiogram is practically identical with the pre-shock electrocardiogram. Many sheep have been observed for periods of months after recovery from fibrillation, with no evidence of abnormalities. Several have given birth to normal lambs, and in many instances the recovered sheep have been used in subsequent tests and again recovered.

The possibilities of counter-shock have not been fully explored to determine the optimum conditions for its application, particularly as regards magnitude and character of current, its duration, and points of application. In regard to the latter, however, it would seem that some short path embracing the heart would be best. Any technique of recovery of the heart must be applied promptly so as not to permit deterioration of the brain which might result in impairing the competency of the victim if recovered. While the time limit would depend on many factors, it is a matter of minutes rather than seconds. The prompt application of artificial respiration ventilates the lungs and is believed also to maintain a small circulation of blood, sufficient to delay

to give a somewhat higher threshold current. For the pathway from leg to leg, the proportion of current reaching the region of the heart is so small that fibrillation is not liable to result, even at currents of 15 amperes or more, although such currents probably would burn the victim unless the contacts were good and the shock of short duration.

*c. Frequency.* For shocks of one second or more in duration, the 25-cycle threshold current is about 25 per cent higher than the 60-cycle value, and the d-c. threshold current 5 times the 60-cycle value. For shock durations of a small fraction of a second this relation probably does not hold, all thresholds being expected to approach one another.

*d. Time of Occurrence of Short Shocks in Relation to Cardiac Cycle.* The heart is most sensitive to fibrillation for shocks occurring during the partial refractory phase of its cycle, which is about 20 per cent of the whole and which occurs simultaneously with the *T* wave of the electrocardiogram. With shocks of a duration of about 0.1 second or less, it is practically impossible to produce ventricular fibrillation, unless such shocks coincide in part at least with this sensitive phase of the cardiac cycle. The middle of the partial refractory phase is more sensitive than its beginning or end.

*e. Duration of Shock.* The threshold current varies inversely with shock duration but not uniformly, being most sensitive to change as the duration approaches the duration of one heart beat. Within the sensitive phase of the heart cycle the threshold fibrillating current for shock durations of about 0.1 second or less is 10 or more times the threshold for durations of one second or more. Shocks ⅓ or more of the heart cycle in duration may cause ventricular fibrillation, even though they would not extend into the sensitive phase of the cycle if the heart continued its normal beat after the initiation of the shock. The reason for this is probably the initiation of a premature heart beat which brings about a premature sensitive phase prior to the end of the shock.

5. Successive shocks have no cumulative effect on the susceptibility of the heart to fibrillation.

6. The susceptibility of the heart to fibrillation by short shocks increases with current up to several times the threshold, then diminishes, becoming very small at currents of the order of 25 amperes through the body in the vicinity of the heart. However, other serious injury may be expected from such currents when brought about by accidental contacts.

7. Fibrillation produced by an electric shock will in the majority of cases be arrested by a subsequent electric shock of high intensity and short duration through the heart, allowing the resumption of coordinate beating with no permanent damage.